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EFFECT OF STRAIN RATE ON THE MECHANICAL PROPERTIES OF CR-MO-V STEEL AT ELEVATED TEMPERATURES

TECHNICAL REPORT

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February 1972

RESEARCH DIRECTORATE

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RESEARCH, DEVELOPMENT AND ENGINEERING DIRECTORATE

U. S. ARMY WEAPONS COMMAND

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The mechanical properties of quenched and tempered Cr-Mo-V steel were determined at temperatures between 800°F and 1300°F at strain rates ranging from 2×10^{-3} to 20/min by the Research Directorate, Weapons Laboratory at Rock Island. Experimental data were analyzed as functions of strain rate and temperature on the basis of three semi-empirical mechanical equations of state. It was found that Cr-Mo-V steel is strain-rate sensitive, and that this strain-rate sensitivity increases with temperature. Deviations in the mechanical behavior of Cr-Mo-V steel from idealized equations are explained on the basis of recovery and recrystallization which take place at elevated temperatures. Despite the deviations, the analysis is useful for the prediction of strength levels of the material at high temperatures and high strain-rates.

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INTRODUCTION

The study of materials to improve the service performance of military hardware is one of the missions of the Research Directorate, Weapons Laboratory at Rock Island, U. S. Army Weapons Command. Since Cr-Mo-V steel is extensively used as a small arms gun barrel material, its mechanical properties at elevated temperatures were studied.

The engineering properties of materials are usually determined at a strain rate of $5X10^{-3}$/min. In many applications, the materials are stressed at a rate considerably higher than that normally recommended for testing. Because the mechanical properties of materials are strain-rate dependent, especially at elevated temperatures,[1] the effect of stresses on materials at different rates of loading must be understood to properly design structural elements, to resolve failure mechanisms, and to evaluate the stability of structures under different loading conditions.

Small arms gun barrels are subjected to cyclic bursts of fire by which the barrel material is stressed at different rates (as high as 10^3 to 10^5/min) over a wide range of temperatures. During firing, the material is heated to a high temperature. With the firing of one shot, the barrel material is subjected to a stress applied at a very high rate. Between two shots, the material is subjected to stresses at a much slower rate because of thermal gradients. During the gradual heating and cooling for each long burst, stresses at still lower rates predominate. If the stresses at crack tips, frictional forces and stresses due to possible phase transformations are considered, the gun barrel material is subjected to different magnitudes of stresses at strain rates ranging over a wide spectrum. Yet, currently in the design of gun barrels, empirical allowances are assigned to compensate for the dynamic stressing of the material.

The experimental results and the analysis of an investigation to determine the mechanical properties of gun barrel steel at elevated temperatures as a function of strain rate are presented in this report. An analysis is included to enable the calculation of strength levels at higher strain rates. The analysis does not purport to accurately predict the mechanical properties of Cr-Mo-V steels under gun barrel environments since the actual strain-rate values are orders of magnitude higher than those utilized for this work, and no allowances were made for the rate of heating and duration for which the specimen is held at temperatures above 1200°F before testing. These

important criteria are lacking, and every attempt should be made to determine the properties of Cr-Mo-V steel under conditions which closely simulate those of a gun barrel during service. This work is the first step in that direction.

EXPERIMENTAL PROCEDURE

Specimen Preparation

All test specimens were machined from the same heat of gun barrel blanks which were quartered in the cross section for the fabrication of test specimens to avoid defects along the axis of the blank. The chemical composition of the test specimens is given below:

C	Mn	P	S	Si	Cr	V	Mo	Cu	Al	Fe
0.41	0.88	0.013	0.014	0.27	1.19	0.22	0.64	0.06	0.03	Rem.

The blanks were subjected to a conventional thermomechanical treatment described below:

1. Normalized at 1700°F for 2-1/2 hours and air-cooled to room temperature,

2. Austenitized at 1575°F for 2-1/2 hours, quenched in circulating oil,

3. Tempered at 1210°F for 2-1/2 hours and air-cooled,

4. Straightened,

5. Stress-relieved at 1100°F for 2-1/2 hours and air-cooled.

The test specimens were degreased, cleaned in alcohol, and stored in a dessicator until the time of testing. The size and shape of the specimen are illustrated in Figure 1.

Testing

Tensile tests were conducted in an Instron Testing Machine at crosshead speeds ranging from 0.002 inch per minute to 20 inches per minute. The experimental setup is shown in Figure 2. Flow curves were recorded autographically.

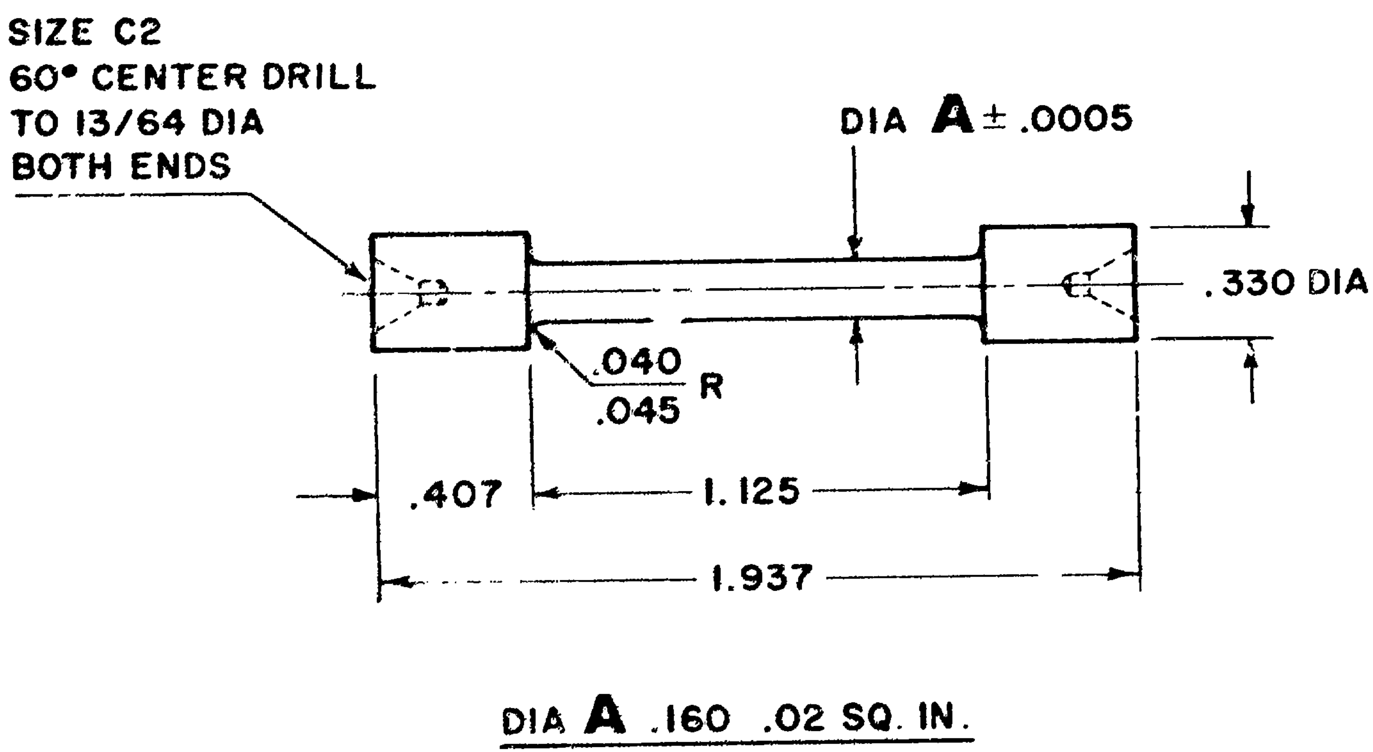

FIGURE 1 Diagram of Test Specimen

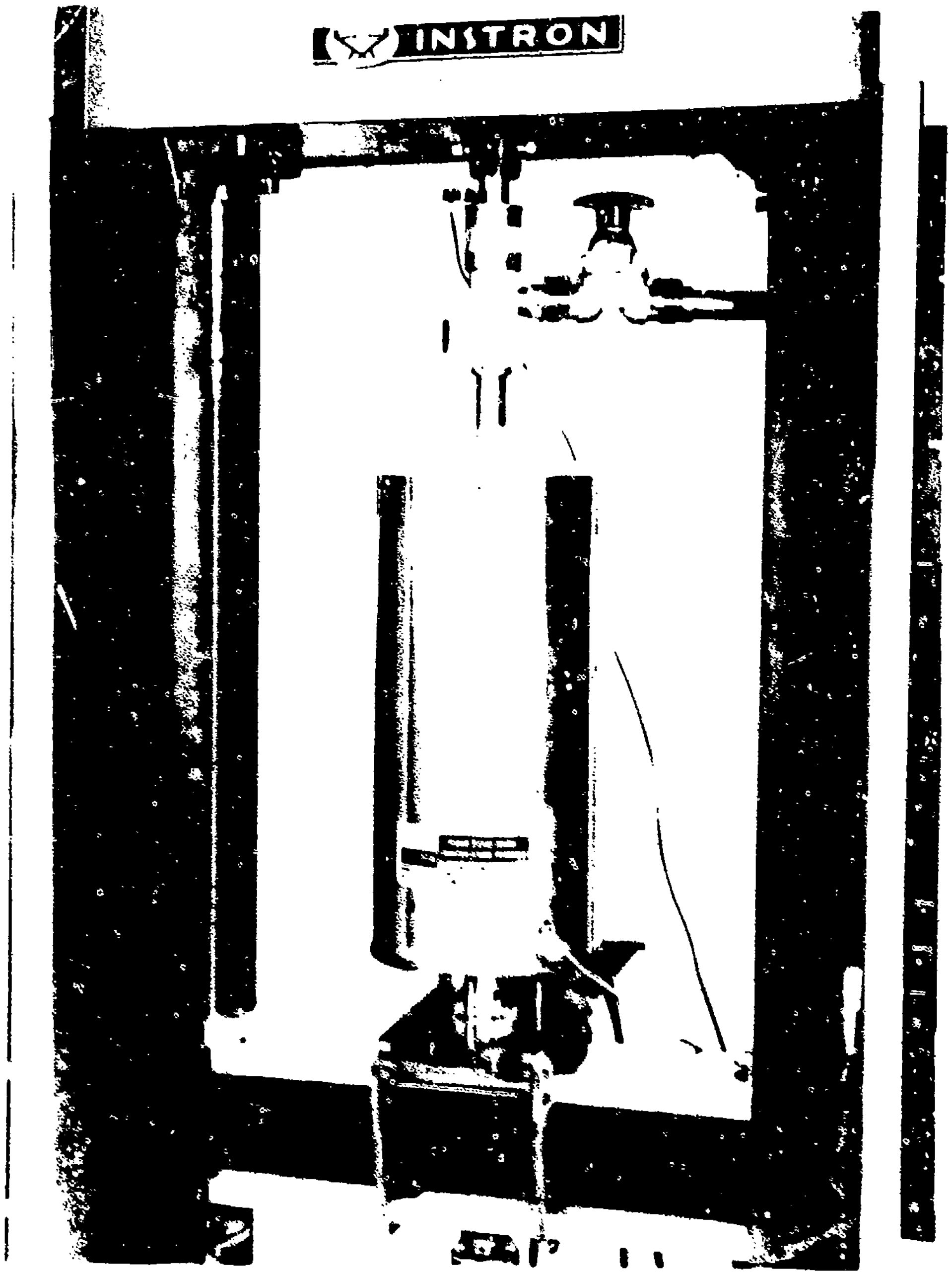

FIGURE 2   Photograph of the Experimental Setup

For crosshead speeds of 5 and 20 inches per minute, the output of the load cell was amplified and recorded as a function of time in a precalibrated oscillograph. Necessary corrections were made to correlate crosshead motion with engineering strain. The specimens were protected from atmospheric contamination by testing them in a vacuum capsule. Temperatures were measured by a platinum - platinum-rhodium thermocouple resting on top of the specimen. The temperature of the specimen could be controlled within ± 5°F of the test temperature. The standard procedure was first to heat the furnace to the test temperature, introduce the vacuum capsule into the furnace and let the specimen gradually become heated to the test temperature. Duplicate tests were conducted at 800, 900, 1000, 1100, 1200, and 1300°F. The minimum cross-sectional area in the neck region was measured with an optical tool analyzer after the specimen was cooled to room temperature. Engineering stresses, strains, and elongations were measured from the autographic records.

The plastic behavior of materials is generally represented as a relation between the true stress $\sigma\varepsilon$ at a constant true strain ε and strain rate or temperature. The true stresses and strains can be calculated from the following relations:[3]

$$\sigma\varepsilon = \frac{P}{A_0}(1 + e) \tag{1}$$

$$\varepsilon = \ln(1 + e) \tag{2}$$

where

P = Applied load
e = Engineering strain
(read off from the autographic records)

ε = True strain

$\sigma\varepsilon$ = True stress at strain ε

A_0 = Original area of cross section of the gage length of the specimen

These relations are true only when the deformation is uniform along the gage length of the specimen, i.e., prior to necking.

RESULTS AND DISCUSSION

Engineering properties were calculated from load-extension records on the basis of the original area of cross section and gage length of the specimen. The values of yield strength (0.2 per cent offset), elongation, and reduction in area are presented in Figures 3 and 4. Qualitatively, the mechanical properties of Cr-Mo-V steel are similarly affected by increases in the test temperature or decreases in the strain rate. The effect of strain rate is significant at high temperatures and low strain rates. At 1300°F, elongation values in excess of 150 per cent have been observed. The tensile specimens after testing at various extension rates at a temperature of 1300°F are shown in Figure 5.

Previous attempts have been made by various investigators to express plastic deformation characteristics of materials as functions of strain rate ($\dot{\varepsilon}$) and temperature (T). Three different methods will be discussed in the following paragraphs with reference to the experimental data obtained from this investigation. The equations developed in the past are semiempirical and have limited applicability. Yet, these equations are helpful in generalizing the plastic behavior of Cr-Mo-V steel, and useful information can be obtained when the relations are used discriminately.

The parameter "true ultimate tensile strength" (true UTS) is chosen for analysis. The reasons for choosing true UTS are discussed by Hart.[4] Values of log (σ_{UTS}) plotted against log $\dot{\varepsilon}$ for the various temperatures are shown in Figure 6. The relation between σ_{UTS} and $\dot{\varepsilon}$ can be represented by the equation

$$\sigma = A\dot{\varepsilon}^m$$

The exponent 'm', which is the slope of the graphs between log (σ_{UTS}) and log $\dot{\varepsilon}$, is usually referred to as the strain rate sensitivity. The strain rate sensitivity increases with temperature. At high temperatures and low strain rates, the linear relationship between log (σ_{UTS}) and log $\dot{\varepsilon}$ is not valid. This is attributed to the onset of dynamic recovery at elevated temperatures while the specimen is being strained. Further reference will be made to this phenomenon. Obviously, in this region of temperature and strain rate, the value of m can be determined only by instantaneous changes in strain rate during testing.

Zener[5] suggested that the flow stress of the material was related to both the strain rate and temperature through

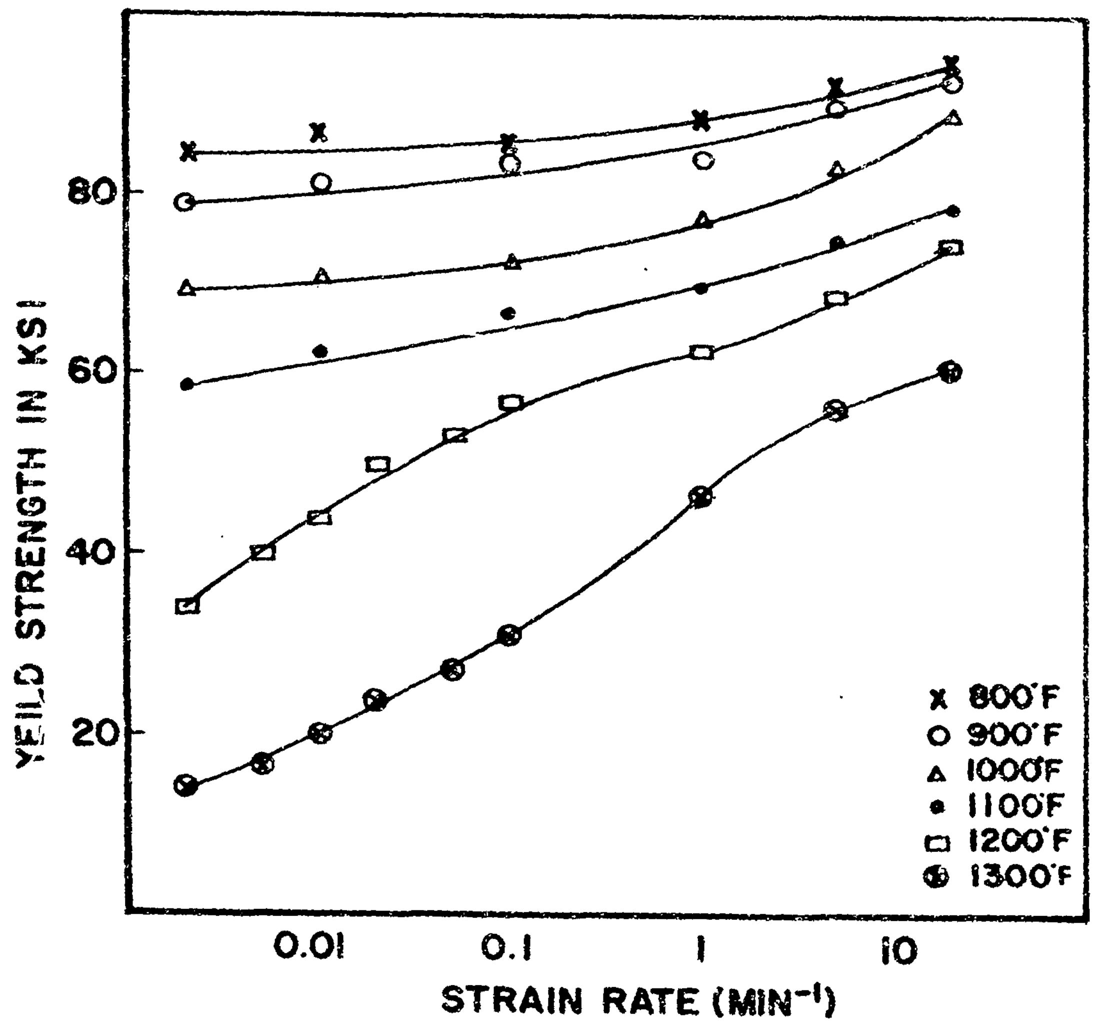

FIGURE 3

Yield Strength of Cr-Mo-V Steel versus Strain Rate at Elevated Temperatures

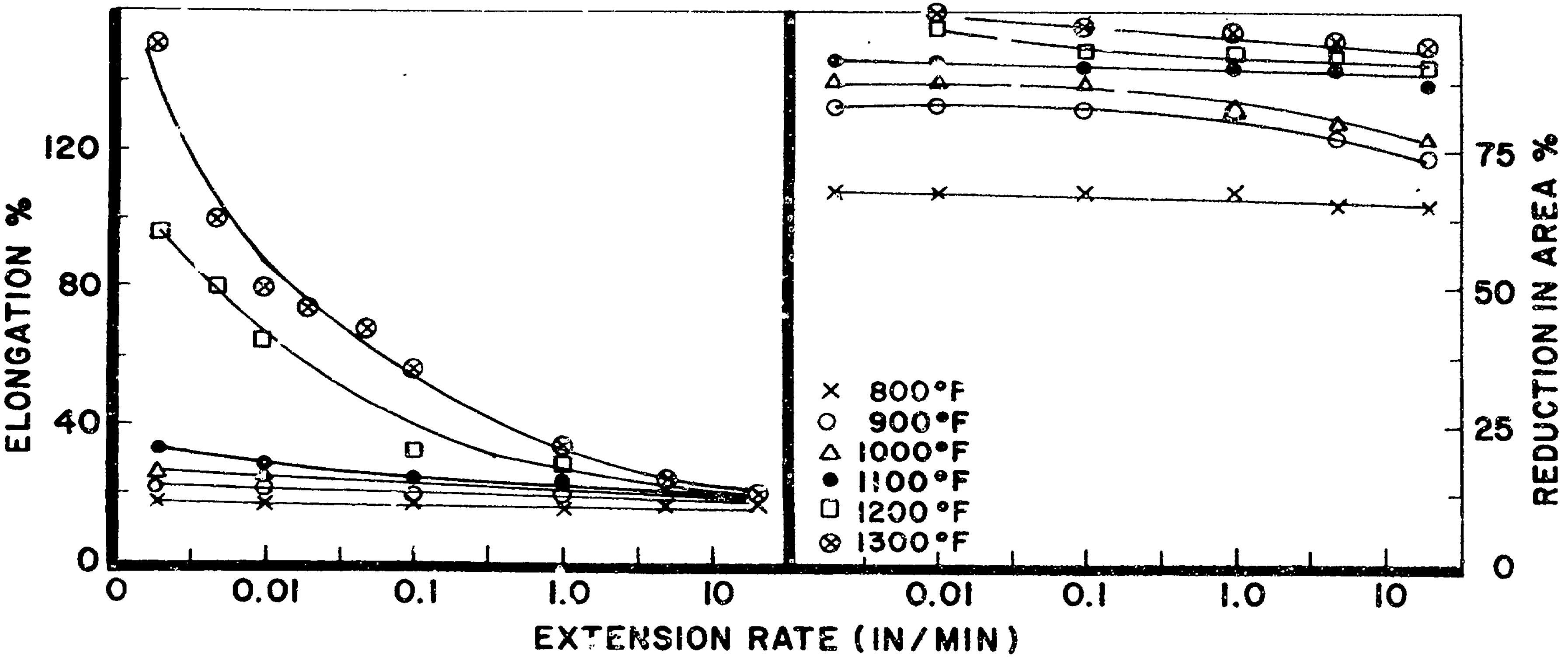

FIGURE 4

Tensile Properties of Cr-Mo-V Steel
at Elevated Temperatures

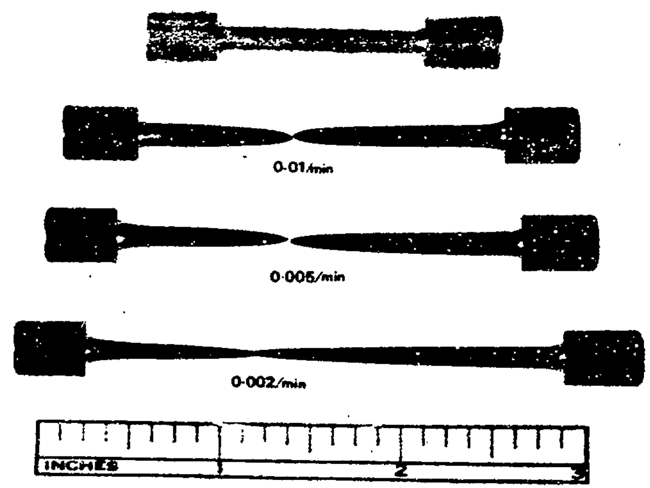

FIGURE 5 Tensile Specimens of Cr-Mo-V Steel Tested at 1300°F

a single parameter P, in the following manner:

$$\sigma = f(P)$$

$$P = \dot{\varepsilon} \exp \frac{Q}{RT}$$

where P is equivalent strain rate and Q is an activation energy.

A graph between $\ln\dot{\varepsilon}$ and 1/T at constant stress should be a straight line with slope Q/R. The value of Q for Cr-Mo-V steel was calculated with the data taken from Figure 6. From a knowledge of the value of Q, P was calculated for each combination of strain rate and temperature. Values of log (σ_{UTS}) plotted against P are shown in Figure 7. Note that the same value of Q is not applicable to regions of high and low P values.

McGregor and Fisher[6] introduced the concept of velocity modified temperature (Tm) in describing the plastic behavior of materials. This concept is based on an absolute reaction rate theory approach to the creep properties of materials. Tm is defined as

$$Tm = T \left(1 - k \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)$$

where the constant k has to be determined from the steady state creep properties of the material. No published information of the creep properties of the gun steel is available at the present time. However, Lubahn[7] has studied the creep behavior of a similar Cr-Mo-V steel. Extrapolated values of steady state creep rates of Cr-Mo-V steel at 800°F and 900°F were used to obtain the value of k. This value k was used to plot σ_{UTS} versus Tm in Figure 8. A functional relationship does appear to exist between σ_{UTS} and Tm.

A close analysis of Figures 7, 8, and 9 reveals that generalized empirical equations do not fully describe the plastic behavior of Cr-Mo-V steel at higher temperatures and lower strain rates. This is to be expected because of the many changes which can take place in the material if it is kept under stress for extended periods of time. Such changes will undoubtedly affect the mechanical properties of the material. One example is shown in Figure 9 in which the load extension records of tensile tests conducted at 1100°F, 1200°F, and 1300°F are reproduced. They clearly demonstrate the onset of dynamic recovery in the material at elevated temperatures.[8,9]

Despite these limitations, the graphs in Figures 7, 8, and 9 can be used to predict the strength of Cr-Mo-V steel at elevated temperatures and at high strain rates.

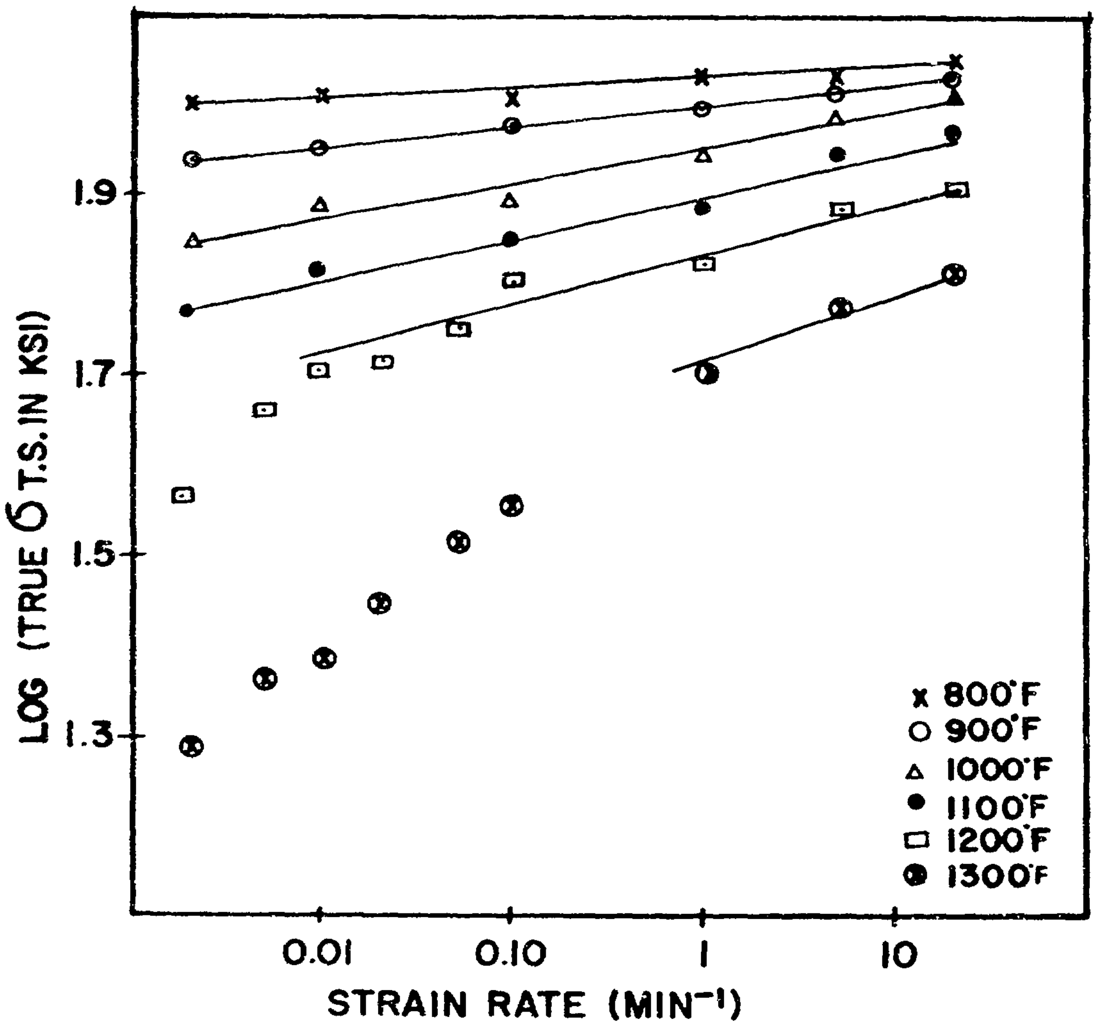

FIGURE 6

Tensile Strength of Cr-Mo-V Steel
versus Strain Rate at Elevated Temperatures

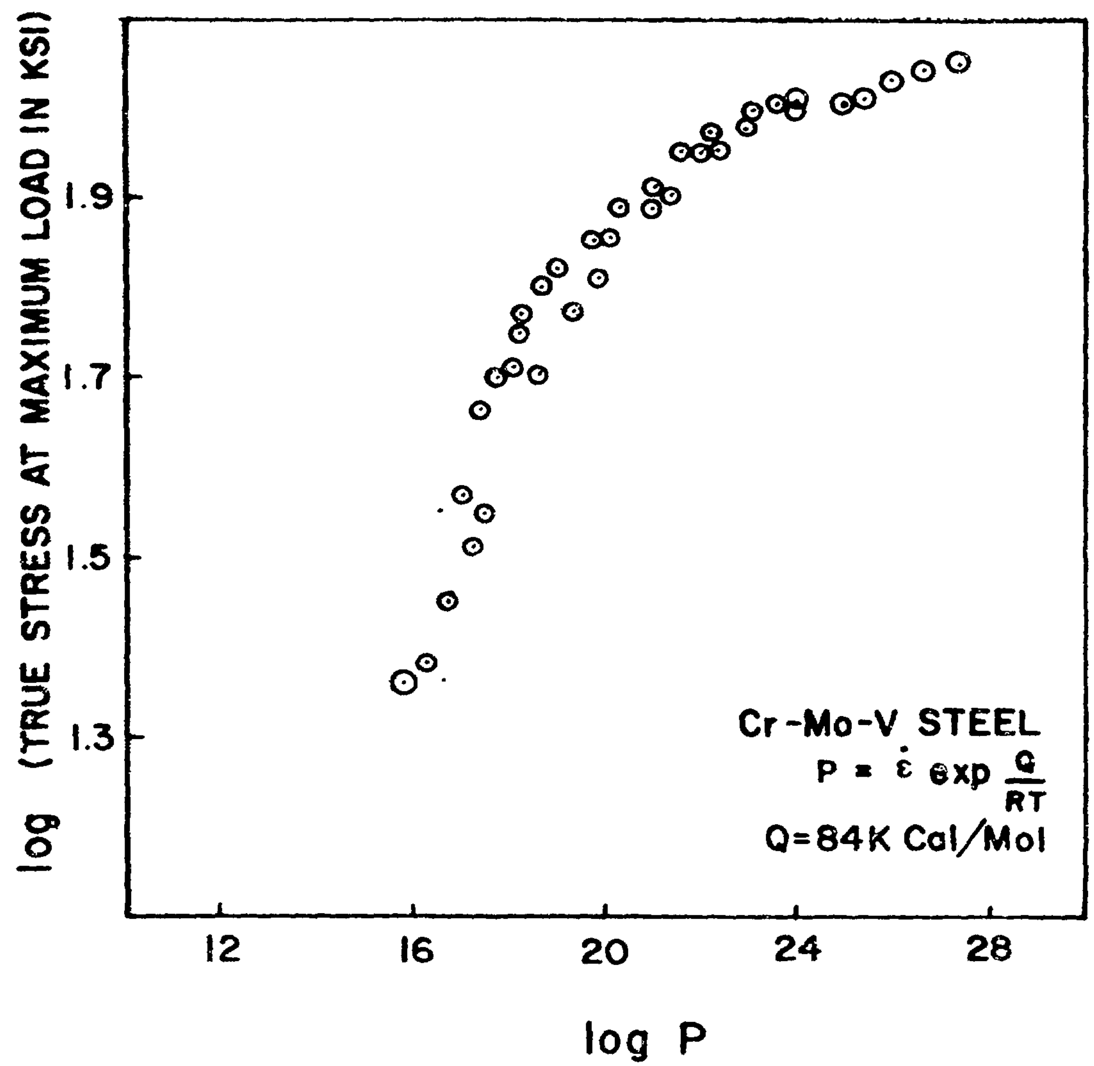

FIGURE 7 Stress and Equivalent Strain Rate for Cr-Mo-V Steel

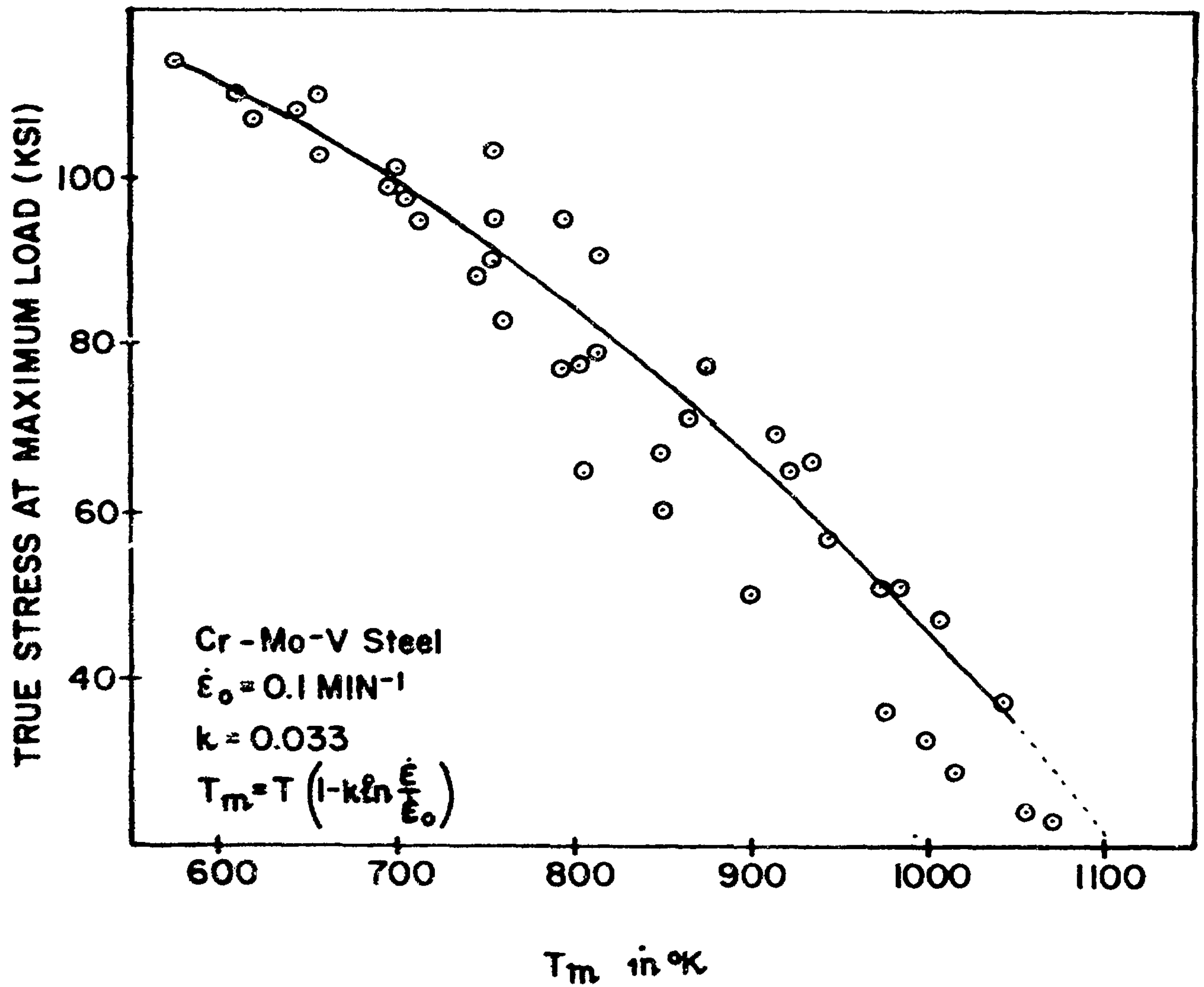

FIGURE 8 Stress and Velocity-Modified Temperature for Cr-Mo-V Steel

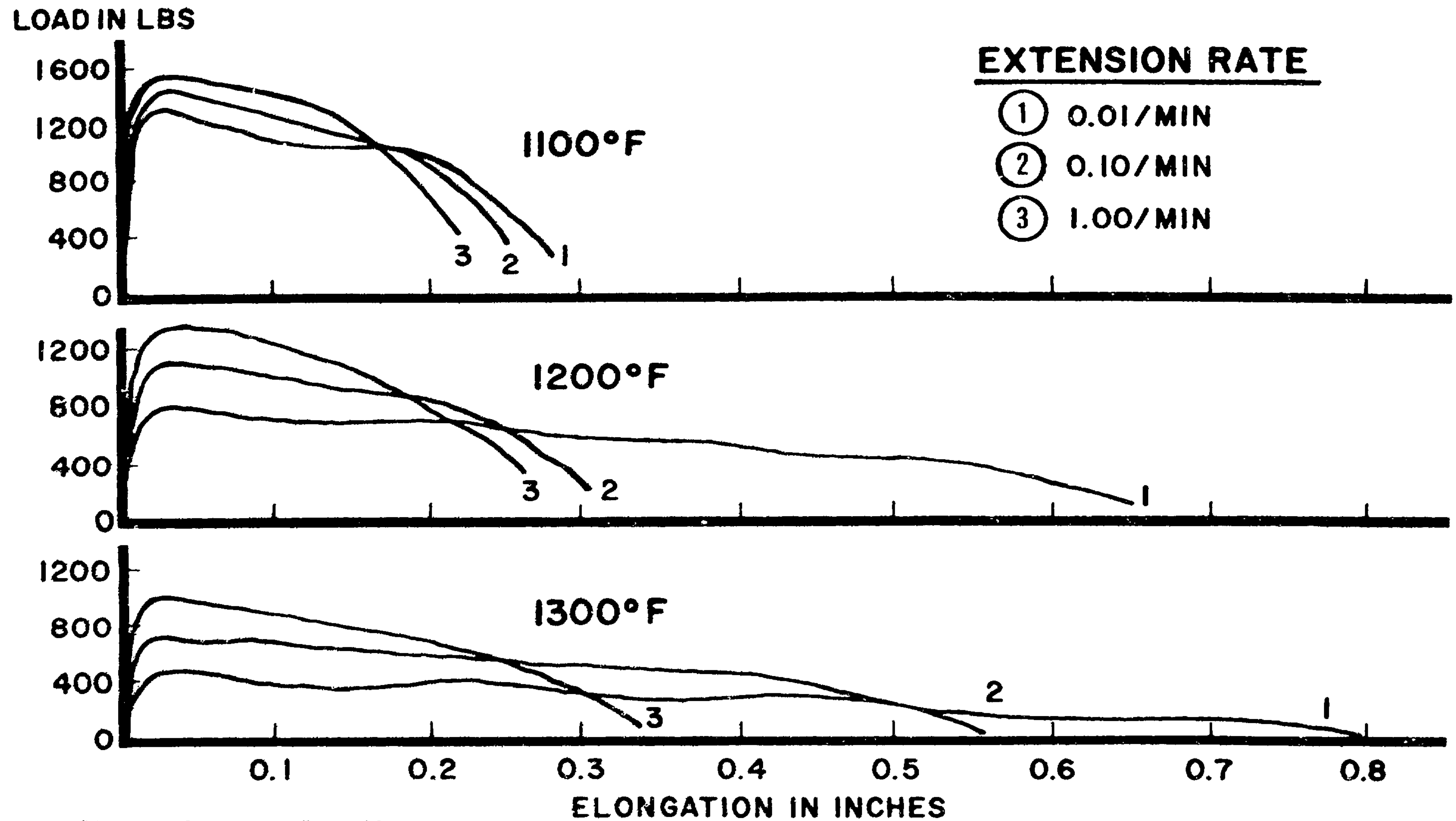

FIGURE 9 Tensile Load-Deformation Diagrams for Cr-Mo-V Steel

CONCLUSIONS

1. The mechanical properties of quenched and tempered Cr-Mo-V steel are strain rate sensitive and the strain rate sensitivity increases with temperature.

2. The concepts of "equivalent strain rate" and "velocity modified temperature" have limited applicability for the description of the mechanical properties of Cr-Mo-V steel.

3. The deviations from semiempirical relations by which the mechanical behavior of Cr-Mo-V steel is described occur at high temperatures and low strain rates.

4. Such deviations are attributable to microstructural changes and dynamic recovery which take place at elevated temperatures when sufficient time is allowed.

FUTURE WORK

1. The mechanical behavior of Cr-Mo-V steel at high strain rates will be investigated by the Research Directorate, Weapons Laboratory at Rock Island.

2. Cr-Mo-V steel shows increased dependence of strain rate sensitivity on strain rate at low strain rates, and enhanced elongation at temperatures above 1200°F. These property characteristics, as well as strain-induced microstructural changes, will be further investigated.

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